Infrared testing of the Wide-Field InfraRed Survey Telescope grism using Computer Generated Holograms

Margaret Z Dominguez[1,2], David A Content[1], Qian Gong[1,2], Ulf Griesmann[2], John G Hagopian[3], Catherine T Marx[1], Arthur L Whipple[4]

[1]NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt MD 20771 USA
[2] National Institute of Standards and Technology, Physical Measurement Laboratory, Gaithersburg, MD 20899 USA
[3] Sigma Space Corporation, 4600 Forbes Boulevard, Lanham, MD 20706 USA
[4] Conceptual Analytics LLC, 8209 Woburn Abbey Rd, Glenn Dale, MD 20769 USA
margaret.z.dominguez@nasa.gov

Abstract: Infrared Computer Generated Holograms (CGHs) were designed, manufactured and used to measure the performance of the grism (grating prism) prototype which includes testing Diffractive Optical Elements (DOE). The grism in the Wide Field Infrared Survey Telescope (WFIRST) will allow the surveying of a large section of the sky to find bright galaxies.

OCIS codes: (120.0120) Instrumentation, measurement and metrology; (120.3930) Metrological instrumentation

1. The WFIRST grism prototype

WFIRST is a NASA observatory which will study dark energy, exoplanets and infrared astrophysics. It will have a field of view about 90 times bigger than the Hubble's Advanced Camera and approximately 200 times bigger than Hubble's IR channel of the Wide Field Camera 3. This capability will enable it to capture more of the sky with less observing time. This is also possible due to slitless spectroscopy done with the grism, which will allow the surveying of a large section of the sky to measure spectra of bright galaxies and redshift to allow three dimensional surveys [1].

The three-element grism consists of three fused silica elements with diffractive surfaces on two of the elements. It has a spectral range of 1.35- 1.95 µm. The designed grism wavefront error is diffraction limited across the bandpass. Even though each individual element is highly aberrated, when assembled they become diffraction limited due to the compensations among them. The main challenge with the grism is the optical design due to its wide field of view (FOV), large dispersion, and relatively small f/#. Another challenge is to make high efficiency diffractive surfaces. The main challenge is solved using an innovative optical design with two diffractive surfaces. The second challenge is solved by using the latest microlithography techniques from the semiconductor industry and by early interaction with vendors.

Each of the elements was made of fused silica (Corning 7980), each has different specifications and functions. Element 1 (E1) has a spherical front surface and flat back surface with a diffractive pattern on it and is wedged. E1 is meant to correct the wavelength scaled aberration from the grating in non-collimated space. Element 2 (E2) is a bi-concave optic with a wedge. Its function is to deviate the beam to make the assembly zero deviation. Element 3 (E3) also has a spherical front surface and flat back surface with a diffractive pattern on it, but does not have a wedge. Its function is to provide the required spectral dispersion for the instrument [2]. In order to measure each individual optical element a testing procedure for each one was developed. Since E1 and E3 have similar shapes (plano-convex with a grating on the flat side) these followed a similar testing procedure, even though their grating patterns were manufactured by different vendors using different techniques. This paper will focus on the design and manufacturing of the infrared CGHs used to measure elements 1 and 3 and the results obtained.

2. Designing and manufacturing the CGHs for E1 and E3

The elements performance needs to be measured in the 1.35- 1.95µm range because of its wavelength dependent diffraction efficiency. In this wavelength range multiple verification tests need to be conducted, including spectral resolution, diffraction efficiency and imaging capabilities. The latter was done using an infrared interferometer in collimated space and compatible infrared CGHs. The advantage of having the CGH in collimated space is that the placement of the CGH relative to the interferometer is not sensitive.

A CGH is a diffractive null lens that has been used for measuring aspheric optical surfaces together with an interferometer. An incident wavefront is converted by the CGH to an aspheric wavefront that matches the shape of the ideal surface under test, resulting in a null test setup [3, 4]. The CGH changes the wavefront of the incident beam via diffraction caused by a phase grating on its surface. It consists of line patterns on a flat wafer and is usually binary. There are two types of binary CGHs: amplitude and phase. The latter has higher diffraction efficiency.

CGHs are very useful when testing non-conventional optics, like those with grating patterns, however working with them comes with disadvantages, most notably, unwanted diffraction orders. The unwanted orders form ghost fringes which reduce measurement accuracy if not fully blocked. Additionally, using an optic with a DOE to test another optic with a DOE can be complicated and additional validation and modeling of the test setup is required. Some of these disadvantages can be overcome by separating the diffraction orders by adding carriers, either a tilt carrier for lateral separation, or a power carrier for longitudinal separation. Phase CGHs were used to measure the grism individual elements, which have the highest diffraction efficiency of the wanted order (usually the 1st order). In the CGH design process efforts were spent on eliminating the ghost fringes from the unwanted orders.

Initially, after completing their design in-house, visible light amplitude CGHs were fabricated by a vendor to test E1 and E3. However, their efficiency was too low. In an effort to keep the cost of the CGHs down and to have control of the time, manufacturing process and additionally learn this manufacturing process, it was decided that we would make our own phase CGHs.

The CGHs were designed in Zemax by optimizing a Zernike Fringe Phase surface at 1.55µm, the center wavelength of the operational range of the instrument. These had three different sections, two of which were made to be used with visible light which also originated from the interferometer. These were alignment aides, one in the center in the other one at the edge, which looked like a ring. Plus they had additional orientation features. The third section, which meant to resolve the null test pattern was designed to work with the interferometer's infrared light. Also, they were made to work in collimated space for ease of alignment with respect to the instrument. Once the Zernike Coefficients [5] were determined over the normalization radius, they were converted into a GDS (Graphic Data System) format file.

This file was then read by a laser writer, which wrote the pattern onto a quartz 6x6" square photo mask, 6mm thick with chrome and photo-resist. Once it was written, developed, and chrome etched, it was dry etched by a Reactive Ion Etching machine. An ideal etch depth was calculated [6] beforehand and a recipe at the etcher was developed for this specific material, so that the photo mask would be etched at the required depth to achieve the efficiency needed. During the development of the recipe a profilometer was used to determine the rate of the etching depth. Once the appropriate depth was obtained, the CGHs were stripped of photoresist for completion. Figure 1 shows the final CGH used to measure E3.

3. Testing E1 and E3

Two CGHs were made, one for E1 and one for E3. Additionally, two interferometers were used to measure the individual elements. At NIST, the IR3 interferometer was originally developed for thickness measurements of silicon wafers [7]. It has wavelength and piezo-mechanical shifting capabilities with a 6" diameter transmission flat which also has some tuning capabilities with respect to wavelength. A Zygo commercial wavelength shifting interferometer (λ = 1550nm) with a 4" diameter transmission flat was also used. E1 and E3 were measured in collimated space in a double pass setup with a return flat after the test element. Figure 1 shows the designed and test layout for testing E3.

The IR3 used a single-mode tunable diode laser with a wavelength range centered at 1550 nm. The piezo-mechanical shifter had a range of about 420° at 1550 nm, sufficient for basic phase shifting algorithms. The mechanical phase shifting algorithm used seven samples and 60° phase shift between samples. When doing wavelength phase shifting, a phase shifting algorithm with 13 samples and 60° phase increment between samples was used. Due to the long cavity, the wavelength change required for the 4π phase shift was very small.

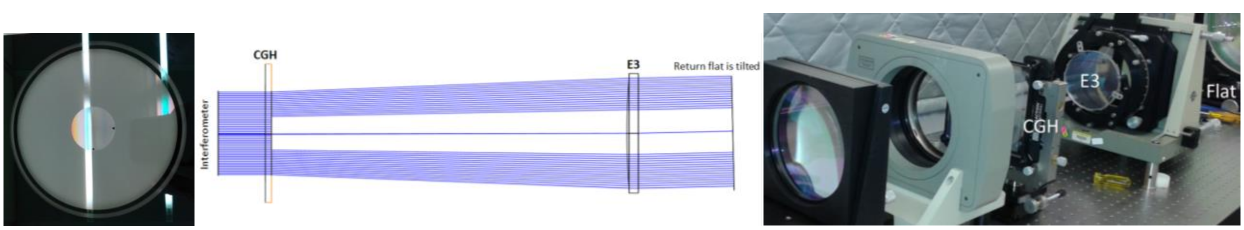

Fig. 1. Left: CGH made at NIST for E3 testing. Center: Zemax layout of CGH measuring E3 with return flat.
Right: Actual test setup of E3 at NIST with IR3, where the interferometer is not in the picture.

IR3 was able to measure the full aperture of the elements and due to its dual capability it could validate that a wavelength shifting interferometer can successfully measure an optic with a diffractive surface. The results from IR3 showed that both techniques yielded the same result. Table 1 compares the measured wavefront errors with both interferometers and it demonstrates that the wavelength shift for a long optical path length works as well as phase shifting. The wavelength change during wavelength shifting does not cause significant measurement errors, even when measuring an optic with a DOE. Modeling results show that for an approximate wavelength shift of 0.01nm, this introduces a WFE in the order of sub-nanometers, making it negligible.

The wavefront error from the Zygo is different, which might be largely due the fact that the measured wavelength of the interferometer was 1.5445µm, which is off from the claimed 1.55µm, which was used to design the CGHs.

Table 1. Measured wavefront error of E1 and E3 with IR Zygo and IR3 interferometers

WFE comparison	Zygo Wavelength shifting	IR3 Wavelength shifting	IR3 Piezo shifting
Element 1	86.9 ± 4.2	63.1 ± 0.9	62.2 ± 1.1
Element 3	55.7 ± 5.9	57.5 ± 0.6	57.3 ± 0.8

Because the CGH was used in collimated space, a transmission flat was inserted with negligible additional aberration. When the beam passed the CGH, it slowly diverged to match the power of the element being measured, meanwhile the same amount of aberration with opposite sign was generated to cancel the aberration of the test element. Figure 2 shows the wavefront maps measured for E1 by IR3 and Zygo. All wavefronts were analyzed with MX Zygo software, so that the same fitting algorithm was used on all the data. The results show that both elements meet the design requirements and results are close enough to meet the assigned error in the error budget. Since it is known that when all elements are assembled their performance is diffraction limited, their individual performance does not have to be so good, due to the compensations among them.

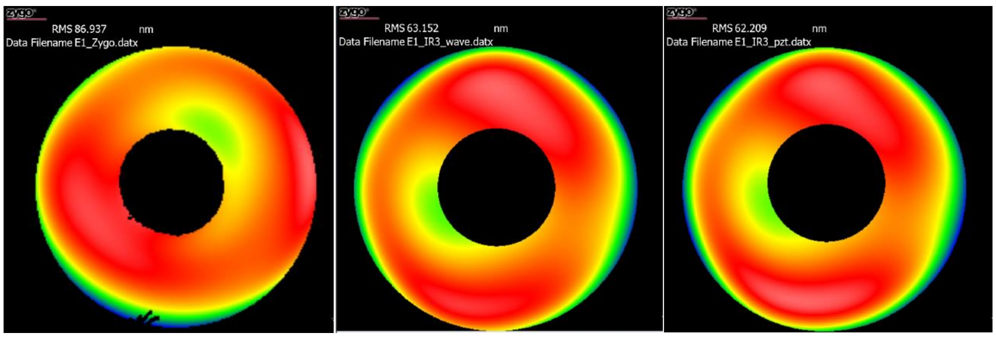

Fig. 2. Measured wavefront maps for E1.
Left: Zygo measured. Center: IR3 measured via wavelength shifting. Right: IR3 measured via piezo shifting.

4. Summary

It has been shown how infrared CGHs were designed and manufactured in-house and were then used to measure the wavefront of E1 and E3. Results indicate that the elements have acceptable wavefront errors. The CNST at NIST used a laser writer and plasma etcher to make phase CGHs. Access to this laboratory has not only greatly shortened test turnaround time, but also provided flexibility to learn the manufacturing process and reduce cost.

5. Acknowledgments

Manufacturing the CGHs was possible because of the use of the facilities at the NIST (National Institute of Standards and Technology) CNST (Center for Nanoscale Science and Technology). This center provides access to world-class nanoscale measurement and fabrication tools, with a staff that trains any user interested in using their facilities.

6. References

[1] Content, D., et al. "Wide-Field InfraRed Survey Telescope (WFIRST) 2.4-meter mission study." SPIE UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VI. San Diego: SPIE Proceedings, 2013. 7.

[2] Gong, Qian, et al. "Wide-Field InfraRed Survey Telescope (WFIRST) slitless spectrometer: design, prototype and results." Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave. Edinburg: SPIE, 2016. 18.

[3] Malacara, Daniel. Optical Shop Testing. 3rd. Wiley-Interscience, 2007.

[4] Burge, James, Chunyu Zhao and Ping Zhou. "Interferometric Testing of Optical Surfaces." Digital Optical measurement, techniques and applications. Norwood: Pramod Rastogi, 2015. 42.

[5] Goodwin, Eric P and James C. Wyant. Field Guide to Interferometric Optical Testing. SPIE Press Book, 2006.

[6] Barbastathis, George and Colin Sheppard. "MIT open courseware." 6 March 2009. Lecture 16: Gratings: amplitude and phase, sinusoidal and binary. <http://ocw.mit.edu/courses/mechanical-engineering/2-71-optics-spring-2009/video-lectures/lecture-16-gratings-amplitude-and-phase-sinusoidal-and-binary/>.

[7] Griesmann, Ulf, et al. "Manufacture and Metrology of 300 mm Silicon Wafers with Ultra-Low Thickness Variations." Characterization and Metrology for Nanoelectronics: 2007 International conference on Frontiers of Characterization and Metrology. Washington, DC: International Conference of Characterization and Metrology, 2007. 6.